

OPTICALLY CONTROLLED SWITCHES

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to photosensitive electrical devices.

5 Discussion of the Related Art

Many complex systems use electrical control circuits to operate other devices. Some such electrical control circuits use photosensitive materials to control the currents or voltages therein. The photosensitive materials include semiconductors such as gallium arsenide (GaAs).

10 In a semiconductor, light of an appropriate wavelength optically excites mobile carriers. The optical generation of mobile carriers reduces the resistance of a channel made of the semiconductor. The optically induced change in channel resistance has been used as a trigger for such electrical control circuits.

15 SUMMARY OF THE INVENTION

When a conventional semiconductor is not illuminated, the material still has a significant conductivity. Thus, a channel made from a conventional semiconductor typically supports a significant leakage current when not illuminated. Due to the high leakage current, a conventional semiconductor channel does not function like optically
20 controlled switch.

Various embodiments according to principles of the invention provide a photosensitive switch. The photosensitive switch has a conducting state in which the switch supports a substantial current and an insulating state in which the switch supports, at most, a low leakage current. The photosensitive switch goes rapidly from the
25 insulating state to conducting state when illuminated by light of an appropriate wavelength. The photosensitive switch is advantageous as a regulator for a high voltage source, because the switch passes, at most, a low leakage current when not illuminated.

One optically controlled switch according to principles of the invention includes first and second electrodes, a channel extending between the electrodes, and a light
30 source. The channel includes a photosensitive organic material. The light source is

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capable of illuminating the entire length of the channel and of changing the channel from an insulating state to a conducting state.

BRIEF DESCRIPTION OF THE FIGURES

5 Figure 1 is a cross-sectional view of an optically controlled switch;
Figure 2 shows a control circuit based on the optically controlled switch of Figure 1;

Figure 3 is a flow chart for a method of operating the optically-based control circuit of Figure 2; and

10 Figure 4 is an oblique view of a micro-electromechanical (MEM) device that uses the optically-based control circuit of Figure 2.

In the Figures, like reference numbers refer to functionally equivalent elements or features.

DETAILED DESCRIPTION OF THE EMBODIMENTS

15 Figure 1 shows an optically controlled switch 10. The switch 10 includes a photosensitive switch 12 and a light source 14. The photosensitive switch 12 is based on a planar structure. The planar structure includes an insulating substrate 16, two electrodes 18, 20 located on the substrate 16, and a photosensitive layer 22 that overlays
20 both electrodes 18, 20 and the substrate 16. The light source 14 produces light with a wavelength that is adapted to change the resistivity of the material in the photosensitive layer 22.

In the planar topology, the thickness of photosensitive layer 22 is less than the length of channel region 26. Also, light source 14 transmits light in a direction transverse
25 to the conduction direction, L, in channel region 26. Thus, the light is able to penetrate the entire length of the channel region 26 even if the channel region 26 is long.

For switch-like behavior, the ratio of the resistance of channel region 26 when illuminated, i.e., bright state, to the resistance of the channel region 26 when not
30 illuminated, i.e., dark state, must be at least 10^4 , preferably is at least 10^6 , and more preferably is 10^8 or more. To obtain such a high ratio of resistances, the entire length of the channel region 26 must be illuminated by light source 14 in the bright state. If a small

transverse section along the channel region 26 remains insulating in the bright state, the resistance of that portion will dominate the entire channel resistance, because the resistivity of the channel material is orders of magnitude larger in the insulating state than in the conducting state. Thus, if a small section along the length of the channel region 26 remains non-illuminated, the ratio of the dark-state resistance to the bright-state resistance will not have the larger values characteristic of switch behavior.

This should be contrasted with a stacked topology common to solar cells (not shown). In a stacked topology, incident light propagates along the direction of current flow in the channel region. The length of the channel region must be short if light is to penetrate the entire length of the channel region.

In the planar topology, channel region 26 may be as long as desired without interfering with the ability of light source 14 to illuminate the entire channel region 26. In contrast with the stacked topology, the planar topology enables the channel length to be long enough to provide a high channel breakdown voltage without interfering with the need for the whole channel region 26 to be conducting in the bright state. Exemplary breakdown voltages for channel region 26 are at least 50 volts, preferably at least 100 volts and more preferably at least 300 volts.

The planar topology also allows channel region 26 to have a dark-state electrical resistance characteristic of switch behavior, i.e., due to the long channel length.

Exemplary channel regions 26 have dark-state resistances of at least 10^7 ohms, preferably at least 10^8 ohms, and more preferably 10^9 ohms or more. These large resistances insure that photosensitive switch 12 has a very low leakage current in the dark state.

In Figure 1, the electrodes 18, 20 are made of gold (Au), aluminum (Al), indium-tin-oxide, titanium nitride (TiN), heavily doped silicon, or other conductors. In preferred embodiments, both electrodes 18, 20 are made from the same conductor so that illumination does not photovoltaically produce a voltage across channel region 26.

The material of photosensitive layer 22 has a resistivity that responds to light in a preselected wavelength range. When not illuminated, the photosensitive layer 22 is a good insulator, and when illuminated, the photosensitive layer 22 is a fairly good conductor. For channel region 26, the ratio of the resistance in the dark state to the resistance in the light state is significantly higher than for inorganic semiconductors.

The photosensitive layer 22 includes an organic matrix that is doped with an appropriate electron donor or acceptor to produce a material that conducts when suitably illuminated.

Exemplary organic materials for photosensitive layer 22, include conjugated organic oligomers and polymers such as derivatives of oligomers and polymers containing aromatic units such as phenylenevinylenes, fluorenes, thiophenes, and pyrroles. Exemplary oligomers and polymers of phenylenevinylenes have substitutions of alkoxy or cyano groups off the main chains. Some matrices include copolymers and blends of one or more of the above-described conjugated organic oligomers and polymers.

Preferred organic materials are fully conjugated oligomers and/or polymers that are molecularly aligned to increase the conductivity between electrodes 18, 20 when suitably illuminated. The preferred alignments increase inter-molecular overlaps to provide higher charge mobilities when suitably illuminated, e.g., mobilities of about 10^{-6} cm²/volt-second or more. The matrix molecules may be aligned by stretching a matrix film prior to deposition, quenching the matrix to a liquid crystal state from a liquid state, or depositing the matrix on an alignment layer.

Exemplary dopants for organic matrices include organic oligomers and polymers, inorganic nanocrystals, and organo-metallic complexes. The dopants are either miscible in the organic matrix or chemically bound to the matrix molecules. Upon illumination, the dopants function as either electron donors or electron acceptors for the matrix, which would otherwise be an insulator.

The systems of dopants and matrix molecules belong to one of two classes. In the first class, the dopants are acceptors of photo-excited electrons from the organic matrix or donors of photo-excited holes to the matrix. In the second class, the dopants are photo-excitable donors of electrons to the organic matrix or acceptors of photo-excited holes from the matrix. Photo-excitations can result from the absorption of light by either the matrix molecules or dopants. Each class involves a particular alignment between highest occupied molecular orbitals (HOMOs) and lowest unoccupied molecular orbitals (LUMOs) of the dopants and matrix molecules.

In the first class, the HOMO of the matrix molecules has a higher energy than the HOMO of the dopants, and the LUMO of the matrix molecules also has a higher energy than the LUMO of the dopants. For this alignment of energy levels, dopants have higher electron affinities and higher ionization potentials than matrix molecules. Exemplary of this class are systems in which the matrix includes poly(dialkoxyphenylenevinylene)s and the dopants are selected from C₆₀, metal-phthalocyanines, thia-pyrylium, squarylium, azo-compounds, perylene, anthanthrone, and nanocrystalline CdSe.

In the second class, the HOMO of the matrix molecules has a lower energy than the HOMO of the dopants, and the LUMO of the matrix molecules also has a lower energy than the LUMO of the dopants. For this orbital alignment, the dopants have lower electron affinities and lower ionization potentials than the matrix molecules. Exemplary of the class are systems where the matrix includes poly(α,α' -dicyanophenylenevinylene)s and the dopants are poly(dialkoxyphenylenevinylene)s.

In photosensitive layer 22, dopant concentrations are fixed to produce desired conductivities when suitably illuminated by light source 14. Preferred conductivities result from between about 10¹⁹ and about 10²¹ mobile charge carriers per centimeter cubed when suitably illuminated. To achieve such charge carrier concentrations, organic materials include significant volume fractions of dopants. The volume fraction occupied by dopants is typically greater than 0.1 percent, preferably at least 1.0 percent, and often 10 percent or more.

Light source 14 excites electrons either from dopant sites to the matrix or from the matrix to dopant sites to convert photosensitive layer 22 from an insulating state to a conducting state. Thus, the conductivity of photosensitive layer 22 depends on both the dopant density and the illumination intensity from the light source 14. The dependencies of the conductivity on the dopant density and the illumination intensity are often approximately linear.

The conductivity of channel region 26 varies linearly with both the channel width and the inverse of the channel length. A preselected dark-state resistance fixes the ratio of the width to length of the channel region 26. The dark-state resistance determines the leakage current through the photosensitive switch 12. A desired minimum breakdown

voltage determines the minimum length for the channel region 26 of the photosensitive switch 12.

A person of skill in the art could determine suitable channel dimensions and dopant fractions based on preselected values of the dark-state and light-state channel resistances, the intensity of light source 14, and the channel breakdown voltage.

Figure 2 shows a control circuit 34 based on optically controlled switch 10 of Figure 1. The control circuit 34 includes a direct current (DC) voltage source 36 and a voltage divider 38. In the voltage divider 38, the optically controlled switch 10 and a fixed resistor 40 connect in series. The fixed resistor 40 is a voltage source for a load element 42, e.g., a capacitor or inductor. The resistance of the optically controlled switch 10 controls the current through the fixed resistor 40 and thus, the voltage drop applied across the load element 42.

The optically controlled switch 10 includes light source 14 and photosensitive switch 12 of Figure 1. Exemplary light sources 14 include light emitting diodes (LED) and diode lasers. The light source 14 may include an optical waveguide, e.g., an optical fiber, that delivers light from a remote source to the photosensitive switch 12. A voltage, V, used to modulate the light source 14 controls the resistance of photosensitive switch 12.

Figure 3 is a flow chart for a method 44 of controlling a circuit via an optically controlled variable switch, e.g., switch 12 of Figure 3. The method 44 includes applying an external voltage across a photosensitive switch located in the circuit (step 46). The method 44 also includes modulating the intensity of a light source, e.g. light source 14 of Figure 2, that illuminates the photosensitive organic resistor while the external voltage is applied across the photosensitive organic switch (step 48). The modulated light intensity changes the resistance of the photosensitive switch and thus, the current that the external voltage produces in the circuit. The changed current changes the voltage drop across a load element, e.g., load element 42 in Figure 2.

The induced change in the voltage drop across the photosensitive switch is greater than any photovoltaic voltage induced across the photosensitive switch. Preferably, the change in the voltage drop is at least ten times any produced photovoltaic voltage.

Referring again to Figure 2, exemplary control circuit 34 functions as a digitally modulated (DM) voltage source for load element 42. In the DM voltage source, light source 14 functions as an optical modulator that produces a repeating sequence of bright and dark periods, e.g., ON and OFF periods of a diode laser or LED. The relative lengths of the bright and dark periods are varied to apply different average voltages across fixed resistor 40 and load element 42.

Figure 4 shows a micro-electromechanical (MEM) device 50 controlled by control circuit 34 of Figure 3. The MEM device 50 includes a flexible stalk 52 and a top piece 54. The stalk 52 connects the top piece 54 to substrate 16. The top piece 54 includes a first plate 56 of a capacitor and a reflector 58. A second plate 60 of the capacitor is located on the substrate 16. The capacitor is load element 42 of the control circuit 34 shown in Figure 3. The control circuit 34 determines the charge state of the capacitor thereby controlling the orientation of the reflector 58 on the MEM device 50.

The control circuit 34 functions as a DM voltage source for charging the capacitor that controls the orientation of MEM device 50. In the DM voltage source, light source 14 shines a light beam with a modulated intensity on photosensitive resistor 12. The light intensity is modulated at a frequency that is higher than the time constant for mechanical resonance in the MEM device 50, e.g., at least 5 – 10 times the mechanical resonance frequency. At such high frequencies, the average charge on plates 56, 60 determines the mechanical reaction of MEM device 50 to the driving voltage. The average charge on the plates 56, 60 depends on the relative lengths of the bright and dark portions of the illumination cycle.

Digital modulation of light source 14 requires a high frequency voltage source, V. The voltage source, V, can be a digital source, but the voltage source, V, typically has a maximum amplitude that is much smaller than that of the voltage modulating the charging and discharging of the capacitor of MEM device 50. The voltage applied to capacitor is typically in the range of 0 volts - 1000 volts and is preferably in the range of about 100 volts - 300 volts. For such high voltages, electrically controlled DM voltage sources are often more expensive than the optically controlled DM voltage source formed from control circuit 34 and DC voltage source 36 of Figure 3.

An exemplary DC source 36 has a voltage of about 100 - 300 volts. For such a source a dark-state resistance of about 10^{10} ohms is preferable to avoid substantial power dissipation in the dark-state. For such a resistance, channel region 26 typically has a length of at least 0.5 microns and preferably a length of 1 - 100 microns and a width of about 1,000 microns. The channel region 26 is highly inter-digitated to reduce to overall transverse extend of the region 26 (Figure 4). Such channel dimensions also provide breakdown voltages of in excess of 150 volts.

In other embodiments of system 50, photosensitive switch 12 is replaced by a photosensitive resistor (not shown). The photosensitive resistor has a photosensitive channel region 26 that includes either organic or inorganic materials. Exemplary inorganic materials include amorphous selenium (Se), silicon (Si), cadmium sulfide (CdS), and cadmium selenide (CdSe). These inorganic materials may be doped with well-known electron acceptors or donors.

Other embodiments of the invention will be apparent to those skilled in the art in light of the specification, drawings, and claims of this application.

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